

Microensing Maps for the Galactic Bulge

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ABSTRACT

Microensing maps – that is, contours of equal numbers of events per 10^6 source stars – are provided for the inner Galaxy under two alternative hypotheses : (1) the bulge is an oblate axisymmetric spheroid or (2) the bulge is a prolate bar. Oblate spheroids yield a total of ~ 12 events per year per 10^6 stars at Baade’s Window (~ 15 events if the disk is maximal). The event rate is slightly lower for prolate bars viewed at $\sim 45^\circ$ and the maps have a characteristic asymmetry between positive and negative longitudes. Prolate bars can yield mild amplifications of the event rate if viewed almost down the long axis. The disk provides the dominant lensing population on the bulge major axis for $|\ell| \gtrsim 6^\circ$. Measurements of the rate at major axis windows can test for disk dark matter or maximal disk models.

Subject headings: dark matter – Galaxy: stellar content – Galaxy: structure – gravitational lensing

1. INTRODUCTION

The startling reports of enhanced rates of microlensing towards the Galactic bulge (Alcock et al. 1994, Udalski et al. 1994a, Udalski et al. 1994b) confront us with immediate challenges. Are the observations consistent with the known populations of deflectors? Do the microlenses lie in the Galactic disk or in the bulge or even – as recently suggested by Paczyński et al. (1994) – in a bar? The aim of this Letter is to suggest observational tests that can provide answers to these questions.

2. BULGE, BAR AND THICK DISC MODELS

Let us first introduce models for the components of the inner Galaxy. A simple, though idealised, oblate axisymmetric bulge model is provided by Evans & de Zeeuw (1994, hereafter EZ). Their starting point is Becklin & Neugebauer’s (1968) observation that the emissivity profile of the inner bulge is scale-free and falls like $\rho \sim r^{-1.8}$. So, a good representation of the density profile of the cusp is provided by a scale-free oblate power-law model (Evans 1994, hereafter E94). The density of the model is

$$\rho \sim 5.9 \times 10^8 \frac{R^2 + 0.87z^2}{(R^2 + 1.23z^2)^{1.9}} \text{ M}_\odot \text{ kpc}^{-3} \quad (1)$$

where R is the cylindrical polar radius and z the height above the galactic plane in kiloparsec. The model has an apparent axis ratio a_2/a_1 of 0.75 (Habing 1988) and a line of sight velocity dispersion at Baade’s Window of 119 kms^{-1} (c.f. Kent 1992). Outside of the inner kiloparsec, the luminosity density of the galactic bulge falls like $r^{-3.5}$. We do not model this in detail, but truncate (1) at some distance $D_{\text{cut-off}}$, beyond which the density is assumed to vanish. We choose $D_{\text{cut-off}}$ to be 3 kpc so that the total bulge mass is

$\sim 1.9 \times 10^{10} M_{\odot}$. The advantage of EZ’s bulge over Kent’s (1992) hydrodynamical model is that the self-consistent distribution of proper motions for the former is explicitly available (see EZ, Appendix B).

An alternative viewpoint is to regard the bulge as a prolate bar viewed somewhat broad-side on (de Vaucouleurs 1964). A number of investigators have concluded that the evidence from neutral and ionised gas motions (Binney et al. 1991, Blitz & Spergel 1991) and star-counts (Weinberg 1992, Stanek et al. 1994) suggests that the Galaxy is barred. We shall use a prolate power-law model (E94) to represent the bar (c.f., Binney et al. 1991)

$$\rho \sim 3.7 \times 10^8 \frac{x^2 + 0.89(y^2 + z^2)}{(0.67x^2 + y^2 + z^2)^{1.9}} M_{\odot} \text{ kpc}^{-3} \quad (2)$$

Here, the x -axis defines the long axis of the bar, which is oriented at an angle θ to the line joining the Sun to the Galactic Center and the model is truncated at $D_{\text{cut-off}} = 3 \text{ kpc}$. Our bulge (1) and bar (2) models have the same total mass and roughly the same apparent flattening. Although all investigators agree that the near-side of the bar lies at positive Galactic longitudes ($\ell > 0$), there is no concensus over the angle θ at which we view the major axis. Note that EZ’s distribution of proper motions for the power-law models assume the figure is fixed in inertial space. This is a fair approximation if the pattern speed of the bar is small (c.f. Blitz & Spergel 1991).

Lastly, we need a model of the Galactic disk, whose density we assume to be exponentially declining on spheroidal surfaces

$$\rho \sim 3.9 \times 10^8 \exp(-0.29\sqrt{R^2 + 144z^2}) M_{\odot} \text{ kpc}^{-3}. \quad (3)$$

The axis ratio a_2/a_1 is 0.083, as suggested by Bahcall & Soneira’s (1980) analysis. The scale-length of the disk is 3.5 kpc. The normalisation is chosen to recover the local column density of $\sim 50 M_{\odot} \text{ pc}^{-2}$ (Gould 1990). It is sometimes suggested that this data may be misleadingly low. An upper limit is provided by ‘maximal disk’ models, in which disk

matter provides almost all the local centrifugal balance (e.g., Alcock et al. 1994). If the disk is maximal, then the density (3) is roughly doubled. Self-consistent velocity distributions for thick disks are not known – but this is not too serious as the random motions are much smaller than the systemic rotation of $\sim 200 \text{ kms}^{-1}$.

3. MICROLENSING MAPS

The contributions of different deflecting populations can be distinguished by the variation in microlensing rate as a function of Galactic longitude and latitude. A simple way to picture this is provided by *microlensing maps* – that is, contours of equal numbers of events per 10^6 source stars. The maps are useful because they are lots of windows of low extinction towards the bulge. Even along heavily obscured lines of sight, the main effect of interstellar extinction is to reduce the number of detectable source stars. This just alters the overall normalisation of the rate.

The microlensing rate Γ is the reciprocal of the time between events averaged over all possible lensing configurations. So, Γ depends not only on the densities but also the distributions of masses and proper motions of the sources and the deflectors. Kiraga & Paczyński (1994, hereafter KP) introduced a refinement by modulating the density of the sources by a factor of $D_s^{2\beta}$, where D_s is the distance of the source from the sun. This is a crude way of modelling the tendency to observe fewer stars at the far side of the bulge. The value $\beta = -1$ is reasonably close to what is observed (Depoy et al. 1993). To construct microlensing maps, the rate is calculated at any Galactic longitude and latitude (ℓ, b) using eq. (11) of KP. The tangential velocity components of the bulge or bar stars are randomly drawn from the distributions of proper motions of the power-law models (EZ). The distribution of stellar masses is taken as a Gaussian in $\log_{10} M$ for masses greater than

$0.35 M_{\odot}$ and flat below $0.35 M_{\odot}$ to a lower cut-off of $0.01 M_{\odot}$ (Kroupa, Tout & Gilmore 1990).

Figure 1 shows a map for the bulge (1) and disk (3) model of the inner Galaxy. The contributions from the different deflector populations have been separated. The full (broken) contours delineate the number of events per year per 10^6 source stars caused by deflectors in the bulge (disk). If the disk is maximal, then the share from the disk lenses is nearly doubled. The optical depth at Baade’s Window ($\ell = 1.0^{\circ}, b = -3.9^{\circ}$) is 6.3×10^{-7} for microlensing by bulge lenses, 5.0×10^{-7} for disk lenses. The frequency of events is ~ 12 per year per 10^6 stars, of which $\sim 70\%$ are caused by bulge lenses (c.f. KP). This rises to ~ 15 events if the disk is maximal. The unbroken logarithmic contours in the map are almost equally spaced, indicating that microlensing by bulge deflectors declines roughly exponentially with projected distance from the Galactic Center. The broken contours are almost horizontal, confirming KP’s insight that the influence of disk lenses is nearly independent of ℓ . All this suggests a number of observational tests. First, the disk lenses quickly become more important than the bulge lenses on the projected major axis. At the clear window at ($\ell = 12.0^{\circ}, b = 3.0^{\circ}$), maximal disc models yield ~ 11 events per year per 10^6 stars, of which more than 70% are caused by disk lenses. A large event rate measured at major axis windows with $|\ell| \gtrsim 6^{\circ}$ is an unambiguous signature of disk deflectors. A second test is to compare the rate in bulge fields at roughly the same latitude. There are clear windows at ($\ell = 1.0^{\circ}, b = -3.9^{\circ}$) and ($\ell = 5.5^{\circ}, b = -3.5^{\circ}$), which are candidates for the application of this test. The contribution of bulge lenses to the rate varies by $\sim 30\%$, while the contribution of disk lenses remains unchanged. Variation in the rate at locations with the same latitude provides evidence that the deflector population is in the bulge. Inset into Figure 1 are the expected frequencies of event timescales t_0 for the bulge (full lines) and disk (dashed lines) lenses at two fields currently undergoing intense scrutiny – one is at Baade’s window, the other is closer to the Galactic Center ($\ell = 2.3^{\circ}, b = -2.65^{\circ}$). As

Paczynski (1991) and Griest et al. (1991) point out, the average timescale is longer for deflectors in the disk. Notice that this occurs mainly because the dashed distributions have larger tails towards the longer events. At Baade’s Window, the peak timescale is ~ 15 days, irrespective of whether the deflector is a bulge or disk star. This is longer than that found by KP of ~ 10 days. Now, the efficiency of the microlensing experiments cuts off sharply at short timescales. If the distribution is peaked at longer timescales, this may mean that the efficiency has been underestimated, leading to values of the optical depth derived from the experimental results that are too high.

Figure 2 shows a map for the bar (full lines) and disk (broken lines). The position angle of the bar’s major axis θ is chosen as 45° (c.f. Blitz & Spergel 1991). The optical depth at Baade’s Window is 5.3×10^{-7} for bar lenses, 5.1×10^{-7} for disk lenses. The rate is ~ 10 events per year per 10^6 source stars. The map is asymmetric. For bar lenses, the number of events is higher at negative longitudes as compared to positive longitudes. This is because the near-side of the bar lies in the first Galactic quadrant, and so lines of sight to detectable stars for $\ell > 0$ are on average shorter and pass through less of the dense inner bar than for $\ell < 0$. This is analogous to the phenomenon that Crotts (1992) and Gould (1993) noticed for the optical depth of the inclined disks of M31 and the Large Magellanic Cloud. For disk lenses, the reverse is true. The rate is slightly higher at positive longitudes. This is because the rate is averaged over the detectable stars along the line of sight, with nearer sources carrying more weight than more distant sources. For $\ell > 0$, the sources are on average closer, thereby amplifying the rate as compared to $\ell < 0$. This effect is model-dependent and diminishes with increasing β . Udalski et al. (1994b) are already scanning the windows at $(\ell = -5.0^\circ, b = -3.5^\circ)$ and $(\ell = 5.5^\circ, b = -3.5^\circ)$ for possible evidence of the asymmetric microlensing signal of a bar. In our model, ~ 11 events per year per 10^6 sources are expected at the former location, ~ 7 at the latter. Now, Blitz & Spergel’s (1991) estimate of the position angle of the bar’s major axis $\theta \sim 45 \pm 20^\circ$ is in

broad agreement with Weinberg’s (1992) conclusion of $\theta \sim 36 \pm 10$ based on an analysis of the IRAS 2 micron sources. But, both results are in apparent conflict with Binney et al. (1991), who claim $\theta \sim 16 \pm 2^\circ$ from an ingenious analysis of the kinematics of the Galactic Center gas. How does the microlensing rate change as the viewing angle of the bar is varied? The number of events at Baade’s Window is plotted against θ and inset into Figure 2. As we view the bar more nearly down its major axis, the event rate slowly increases to ~ 13 events per year per 10^6 stars (~ 16 events if the disk is also maximal). This is a lower limit of the expected amplification. Our prolate bar (2) looks round when $\theta \sim 0^\circ$ and so does not properly represent the flattening of the bulge. The neglect of the figure rotation and internal streaming motions of the bar might also be expected to lead to an under-estimate of the true rate. Nonetheless, the effect of distending material along the line of sight seemingly causes only a mild enhancement. Even if the bar is viewed at $\theta \sim 0^\circ$, the number of events at Baade’s Window is only just greater than for our oblate axisymmetric model (1). Although it is possible that other bar models exist with greater amplification, the case for interpreting the high optical depths reported by Alcock et al. (1994) and Udalski et al. (1994b) as evidence for a bar remains unproven. Also inset into figure 2 is the asymmetric signal – that is, the percentage fractional difference in the rates at the windows at $(\ell = -5.0^\circ, b = -3.5^\circ)$ and at $(\ell = 5.5^\circ, b = -3.5^\circ)$ – plotted against viewing angle θ . If the bar is seen edge-on or pole-on, this asymmetric signal almost vanishes (not quite, because the windows are not exactly mirror images in $\ell = 0$). But, the asymmetry of the microlensing maps quickly becomes evident as the orientation of the bar is varied. Even if the bar is viewed at $\sim 16^\circ$, the variation in the rates at $(\ell = -5.0^\circ, b = -3.5^\circ)$ and at $(\ell = 5.5^\circ, b = -3.5^\circ)$ is still large enough to be detectable.

4. CONCLUSIONS

Microlensing maps describe the variation in event rate as a function of Galactic longitude and latitude. This is valuable in untangling the contributions of the disk and bulge lenses. We find:

(1) Oblate axisymmetric models of the bulge yield a total of ~ 12 events per year per 10^6 stars at Baade’s Window (~ 15 events if the disk is maximal). Prolate bars can give mild enhancements of the rate if viewed at $\theta \sim 0^\circ$. Slowly rotating prolate bars with inclination angles of $\sim 45^\circ$ have lower rates than oblate models. Unless the bar is seen edge-on or pole-on, the microlensing maps are asymmetric with larger numbers of events expected at negative longitudes as compared to positive longitudes. Overall, the evidence for a bar in the inner Galaxy is strong. So, can the high optical depths reported in Alcock et al. (1994) and Udalski et al. (1994) be explained if the microlenses lie in a bar? Our study of a prolate bar suggests that this is not the whole story, but further modelling with triaxial and swiftly rotating bars is required for a final answer. The efficiency of the microlensing experiments depends partly on the distribution of timescales of events. At Baade’s Window, we find this to peak at ~ 15 days – longer than previous studies (KP). This may mean the efficiency is being underestimated, accounting for some of the discrepancy between theoretical and experimental results.

(2) On the major axis for $|\ell| \gtrsim 6.0^\circ$, the microlensing rate is dominated by contributions from the disk deflectors. So, measurements of the rate at major axis windows test directly for disk dark matter or maximal disk models. For example, maximal disk models provide ~ 11 events per year per 10^6 sources at the clear window at $(\ell = 12.0^\circ, b = 3.0^\circ)$, of which over 70% are caused by the disk lenses.

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FIGURE CAPTIONS

Fig. 1.— Logarithmic contours of equal numbers of microlensing events for the bulge (1) and disk (3) plotted in the plane of Galactic longitude ℓ and latitude b . Unbroken lines depict the contribution from the bulge lenses (respectively 20, 10, 5 and 2.5 events per year per 10^6 stars moving outwards from the centre). Broken lines show the contribution from disk lenses (respectively 5, 2.5 and 1.25 events). The insets show the distribution of events as a function of timescale t_0 for the bulge (unbroken lines) and disk (broken lines) deflectors at Baade’s Window ($\ell = 1.0^\circ, b = -3.9^\circ$) and at ($\ell = 2.3^\circ, b = -2.65^\circ$).

Fig. 2.— Logarithmic contours of equal numbers of microlensing events for the bar (2) and disk (3). The position angle of the major axis of the bar θ is 45° . The unbroken lines are the contributions from the bar lenses, the broken lines are the contributions from the disk lenses. The inset (a) shows the variation of the microlensing rate at Baade’s Window (measured in events per year per 10^6 source stars) with the viewing angle of the bar θ . The inset (b) shows the variation of the asymmetric signal – defined as the percentage fractional difference in the total rate at the clear windows at ($\ell = -5.0^\circ, b = -3.5^\circ$) and ($\ell = 5.5^\circ, b = -3.5^\circ$) – with viewing angle θ . In inset (b), we have not separated the contributions from bar and disk lenses. Of course, the contribution to the asymmetric signal from the disk lenses is almost negligible.

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